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The relationship between executive function, processing speed, and attention-deficit hyperactivity disorder in middle childhood

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The relationship between executive function, processing speed, and attention-deficit hyperactivity disorder in middle childhood

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Abstract

The relationship between executive function, processing speed, and attention-deficit hyperactivity disorder in middle childhood

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ADHD is a heterogeneous disorder that is highly impairing. Early, accurate diagnosis maximizes long-term positive outcomes for youth with ADHD. Tests of executive functioning (EF) are potential tools for screening and differential diagnoses for ADHD; however, previous research has been inconsistent regarding the specificity and magnitude of EF deficits across ADHD subtypes. Here we overcome these limitations by: (1) employing more rigorous methods to conceptualize ADHD in a way that better captures heterogeneity of expression, and (2) by applying a more comprehensive, reliable battery of EF tasks to this association. We tested 1548 children and adolescents (ages 7-15 years) from the Texas Twin Project, a population-based cohort with a diverse socioeconomic and ethnic composition. EF and processing speed were measured in-laboratory with a comprehensive test battery, while ADHD and sociodemographic characteristics were assessed via parent report. We show that EF deficits are isolated to the inattention domain of ADHD. Moreover, we found that the association between EF task performance and inattention remains stable across sociodemographic groups. Our results demonstrate that failures of executive control are selectively manifested as covert inattentive symptoms, such as trouble with organization, forgetfulness, and distractedness, rather than overt symptoms, such as inappropriate talkativeness and interruption. We anticipate that EF tests could be widely useful in clinical and educational settings due to their specificity regarding particular subtypes of ADHD behaviors and their broad predictive validity across key demographic subgroups.

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Chapter 1: Introduction

Attention-Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder that increases an individual's risk for negative outcomes, including poor academic performance, risky sexual behavior, substance use, and earlier mortality (Cuffe et al., 2015; Dalsgaard, Østergaard, Leckman, Mortensen, & Pedersen, 2015; Loe & Feldman, 2007; Usami, 2016). The public and private burdens of ADHD underscore the importance of understanding the disorder's etiology and presentation. Better understanding of the cognitive profiles associated with ADHD has the potential to improve assessment by providing new screening tools that complement traditional approaches based on symptomology alone. The present study investigates the role of cognitive deficits in ADHD, with a particular focus on executive function (EF) and processing speed. We aimed to advance this literature by improving EF measurement and examining the specificity of EF deficits across ADHD subtypes, clinical cut-offs, and sociodemographic groups.

Measurement of EF Deficits in ADHD

ADHD is characterized by persistent difficulties in two domains of behavior: inattention and hyperactivity/impulsivity. Inattention involves difficulty sustaining focus during task performance, lack of persistence, and disorganization. Hyperactivity/impulsivity is characterized by difficulty remaining still or quiet, difficulty delaying gratification, and engaging in potentially harmful actions without considering consequences (National Institute of Mental Health, 2016). In line with the conceptualization of ADHD as a heterogeneous disorder characterized by multiple deficits, the dual-pathway model proposes two pathways to the development of ADHD (Sonuga-Barke, 2003). The motivational pathway involves hypersensitivity to delayed rewards resulting in difficulties with waiting, while the cognitive pathway involves deficits in EF (Sonuga-Barke, 2003; Barkley, 1997), *i.e.*, higher-order cognitive processes that enable goal-directed behaviors (Miyake et al., 2000).

Consistent with the dual-pathway model, individuals with EF deficits are more likely to be diagnosed with ADHD (Seidman, 2006; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). However, the magnitude of the association between ADHD and EF varies depending on how EF is measured. EF domains typically include inhibition (the ability to control prepotent responses), working memory (the ability to maintain information in immediate memory simultaneous with cognitive processing), switching (the ability to efficiently shift attention to different stimuli or rules), and updating (the ability to monitor incoming stimuli and replace old information with new) (Diamond, 2013; Engle, 2002; Engelhardt, Briley, Mann, Harden, & Tucker-Drob, 2015). While performance deficits in working memory and switching have been observed consistently in children with ADHD, relative to children without ADHD (e.g. Rucklidge & Tannock, 2002; Houghton et al., 1999), less consistent associations have been reported for ADHD and inhibition (Elosúa, Del Olmo, & Contreras, 2017).

Inconsistencies in the observed relations between ADHD and EFs may be due, in part, to the use of single tasks when measuring EF (Willcutt et al., 2005; Biederman et al., 2004). This approach can yield unreliable characterization of EF ability, as it is difficult to parse executive demands from other task demands, such processing speed, when using single tasks (Miyake et al., 2000). Individuals with a diagnosis of ADHD do show deficits on multiple measures of processing speed relative to controls (Shanahan et al., 2006; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005). The few studies that considered the joint contributions of EF and processing speed to ADHD found that deficits in single-task EF performance among children with clinical ADHD were not significant after considering performance deficits on individual processing speed tasks (Rommelse et al., 2007).

We overcome this limitation of previous research in two ways. First, we use multiple EF tests and distill executive variance by specifying a latent variable that represents variance in task performance that is shared across tests and lower-order domains (Miyake et al., 2000; Friedman et al., 2008; Engelhardt et al., 2015). This latent EF factor reflects an ability to formulate and maintain goals (Friedman & Miyake, 2017) or a general capacity for controlled attention (Engle, 2002). We also examine the extent to which the general EF factor is associated with ADHD above and beyond processing speed. In this way, the current study aims to provide a detailed characterization of the cognitive deficits within ADHD by examining the relative contribution of higher- and lower-level cognitive processes.

Specificity of EF Deficits

Studies of clinical populations suggest that EF might be differentially associated with ADHD subtypes (inattentive versus hyperactive/impulsive). Findings are inconsistent, however, with respect to which ADHD subtype is associated with executive deficits (Geurts, Verté,, Oosterlaan, Roeyers, & Sergeant, 2005; Nigg et al., 2005;

Chhabildas, Pennington, & Willcutt, 2001). Previous research has focused almost exclusively on clinical populations, but evaluating the specificity of EF deficits to ADHD subtypes can be aided by examining the full range of symptom variation. Molecular genetic evidence has shown that there is a strong correlation between genetic liability towards clinical diagnosis of ADHD and genetic liability toward continuously measured symptoms of hyperactivity/impulsivity and inattention in non-clinical populations ($r >$ 0.9; Demontis et al., 2019). This suggests that the cognitive processes characteristic of populations diagnosed with ADHD might also be relevant to populations with sub-clinical ADHD symptoms. Paralleling advances in the measurement of EF, latent factor models have emerged as a useful tool for advancing understanding of the structure of continuously measured ADHD symptoms in non-clinical populations. Results drawn from this approach support a distinction between inattentive and hyperactive/impulsive symptom dimensions (Arias, Ponce, & Núñez, 2016; Kuntsi et al., 2014; Martel, Roberts, Gremillion, von Eye, & Nigg, 2011; Toplak et al., 2009). Examining the association between EF and continuous variation in these symptom dimensions can, therefore, clarify the specificity of EF deficits.

Beyond cognitive characteristics, another strand of research has considered the role of demographic factors in the development and manifestation of ADHD symptoms. Generally, symptoms of ADHD attenuate with age, potentially due to better self-regulatory ability (Raffaelli, Crockett, & Shen, 2005), and differences in EF between children with ADHD and controls are more pronounced in younger samples (Nikolas & Nigg, 2015). And, some studies have found sex differences in the EF-ADHD association

(Nikolas & Nigg, 2015), although others have found no moderating effects of sex (Seidman et al., 2005; Brocki & Bohlin, 2004). We examined the extent to which EF-ADHD relationships were consistent across age and sex, as well as across race and socioeconomic status (SES). These analyses help to establish the extent to which the relationship between EF and ADHD is broadly generalizable across the population.

Chapter 2: Method

Participants

Participants were 1548 children aged 7.80 to 15.25 (*M*=10.93, SD=1.79, 52.4% female), recruited as part of the Texas Twin Project, an ongoing study of child and adolescent multiples from the greater Austin and Houston areas (Harden, Tucker-Drob, & Tackett, 2013). This sample is ethnically and socioeconomically representative of the surrounding populations: 72.6% of participants identified as non-Hispanic Caucasian, 12.5% as Hispanic/Latino, 4.9% as African-American, 3.4% as Asian, 6.3% as multiple races or ethnicities, and 0.3% as other. Though participants were twins or other multiples, the current study treated them as unique observations; the non-independence of observations arising from individuals being nested within the same family was accounted for across all analyses (see Analyses). *Children whose parents reported they would be unable to complete the written or verbal study tasks were not enrolled in the study. We did not exclude on the basis of any other conditions, including psychiatric diagnoses.*

Measures

ADHD symptoms. Symptoms of inattention and hyperactivity/impulsivity were assessed by participants' parents using 20 items from the Conners-3 rating scales (Conners, 2008). Items were rated on a 4-point scale (from "not at all" to "very often"). Examples of items are '*Doesn't pay attention to details; makes careless mistakes*' for inattention, and '*Acts as if driven by a motor*' for hyperactivity/impulsivity (see Supplementary Table 4 for a list of all items). Parents rated each twin or multiple separately.

ADHD clinical categories. We followed the *Conners-3* scoring guidelines to determine whether individuals met clinical criteria for the following diagnostic subtypes of ADHD: predominantly inattentive [ADHD-IA], predominantly hyperactive-impulsive [ADHD-HI], and combined type [ADHD-C]. Per the Diagnostic and Statistical Manual of Mental Disorders (*DSM-IV-TR*; American Psychiatric Association, 2000), individuals who had six or more symptoms counts in either or both domains met the clinical cut-off for ADHD. Within our sample, 13.7% of participants met the symptom count threshold for any form of ADHD (8.7% Inattentive, 8.4% Hyperactive, 3.4% Combined Type).

Executive functions. The current study included 15 tasks assessing 4 EF domains: inhibition, switching, working memory, and updating (see Supplementary Table 1 for detailed descriptions and reliability statistics of each task). Tasks were administered orally, on the computer, or on paper. *Inhibition* was assessed with four tasks: Animal Stroop (Wright, Waterman, Prescott, & Murdoch-Eaton, 2003), Mickey (Lee, Bull, & Ho, 2013), and Stop Signal. The study originally used an *auditory* Stop Signal task (Logan, Schachar, & Tannock, 1997), which was replaced with a *visual* Stop Signal task (Verbruggen, Logan, & Stevens, 2008) after the third year of data collection to accommodate the needs of administering EF tasks in the MRI scanner. *Switching* was assessed using four tasks: Trail Making (Salthouse, 2011), Local-Global (Miyake et al., 2000), Plus-Minus (Miyake et al., 2000), and a computerized Cognitive Flexibility task (Baym, Corbett, Wright, & Bunge (2008). Cognitive Flexibility replaced the Plus-Minus task, again to accommodate MRI task administration after the third year of data collection. *Working memory* was assessed using three tasks: Symmetry Span (Kane et al., 2004), Digit Span Backward (Wechsler, 2003), and Listening Recall (Daneman & Carpenter, 1980). These tasks tap spatial, verbal, and auditory working memory, respectively. *Updating* was assessed with four tasks: Keeping Track (Miyake et al., 2000), Running Memory for Letters (Broadway & Engle, 2010), 2-Back task (Jaeggi, Buschkuehl, Perrig, & Meier, 2010), and, as a replacement to the 2-Back task after the third year of data collection, a 1- and 2-back task (Jaeggi et al., 2010). Previous research in this sample (Engelhardt et al., 2015; 2016) demonstrated that variation in EF is best captured by a hierarchical factor model, with individual EF tasks loading onto one of four latent factors representing each EF domain and each of these loading onto a common EF factor. This same hierarchical model (see Supplementary Figure 4) was adopted in all the analyses presented in the current research.

Processing speed. Three tasks were used to construct a latent measure of processing speed: Symbol Search (Wechsler, 2003), Pattern Comparison, and Letter Comparison (Salthouse & Babcock, 1991). Each task assessed how quickly and accurately participants identified similarities between symbols, patterns, or letters. See Supplementary Table 2 for detailed description of the tasks and Figure 5 for model parameters.

Sociodemographic characteristics. Parents completed a demographic survey regarding the age, sex, and race of their children, as well as their own sex, race, educational attainment, and household income. A composite index consisting of parent-reported household income and parental education (years of completed education averaged across both parents) was used to represent SES.

Analyses

All analyses were conducted using structural equation modelling implemented with Mplus version 8 software (Muthén and Muthén, 2017). The 'TYPE=COMPLEX' command was used for all analyses to account for non-independence of observations (twins nested within families). The first set of analyses used ordinal item-level data, so weighted least squares estimation was employed in MPlus. Subsequent models used full information maximum likelihood was used to account for missing data. For models using diagnostic categories of ADHD, a Bayesian estimator was specified to allow convergence.

Analyses were conducted in four steps. First, we conducted confirmatory factor analytic models of item-level symptom data in order to determine the best-fitting model for the ADHD symptoms. Five *c*onfirmatory factor models of ADHD were fit and evaluated based on model fit indices (see Supplementary Tables 3 and 5). Model fit was evaluated using the chi-squared test (χ^2), root mean square error of approximation (RMSEA), comparative-fit index (CFI), and Tucker-Lewis index (TLI). Model fit comparisons were conducted using χ^2difference tests.

Second, we parcelled item-level symptom data to avoid estimation issues in subsequent models of ADHD symptoms (Rhemtulla, Brosseau-Liard, & Savalei, 2012). Specifically, symptom parcels were constructed by summing the scores of two or three Conners-3 items, resulting in 10 parcels (5 parcels for each domain; see Supplementary Table 4) that could be treated as continuous variables. The selection of items for each parcel was based on whether the items had similar loadings on the latent ADHD factors in the best-fitting model from the first step. For example, '*Has trouble organizing tasks or activities*' and '*Fails to complete schoolwork, chores or tasks*' showed similar loadings on a inattention factor (λ = .698 and λ = .692, respectively) and were consequently incorporated into the same parcel.

Third, we conducted multivariate regressions that estimated associations between general EF and ADHD outcomes. *T*he main effects of age and sex were controlled for at the level of the first-order EF factors, at the level of the parcels for ADHD, and at the factor-level for processing speed. We estimate separate models that included and excluded processing speed as a covariate.

Fourth, latent variable interaction models (Supplementary Figure 6) were conducted using the XWITH syntax in M*plus* to test whether the associations between EF and ADHD outcomes were moderated by key sociodemographic variables (age, race, sex, and family SES). Given the number of interactions needed to examine the moderating effects at all levels of each sociodemographic variable (7 moderators across each of 3 ADHD domains), we used the Benjamini-Hochberg false discovery rate method (Benjamini & Hochberg, 1995) to correct for effects of multiple testing. FDR-adjusted thresholds for significance were calculated using the *p.adjust* function in R.

Chapter 3: Results

A Bifactor Model is the Best-Fitting Model of ADHD Symptoms

We compared the fit of the following confirmatory factor models of ADHD: (1) a one-factor model, in which all items were regressed onto a single latent ADHD factor; (2) a correlated two-factor model comprised of latent inattention and hyperactivity/impulsivity factors; (3) a correlated three-factor model in which items within the hyperactivity-impulsivity factor were further divided into independent hyperactivity and impulsivity latent factors; (4) a two-dimension bifactor model in which individual items simultaneously loaded onto a general ADHD factor and specific inattention and hyperactivity/impulsivity factors; and (5) a three-dimension bifactor model which further split the hyperactivity-impulsivity residual variance into two distinct factors. Supplementary Table 5 includes the model fit statistics.

The two-dimension a model provided the best fit for the data ($\chi^2(25) = 75.18$, $p <$ 0.001; RMSEA = 0.047, CFI = 0.99; Figure 1). This result is consistent with previous studies (Toplak et al., 2009; Martel et al., 2011).

Inattention, but Not Hyperactivity/Impulsivity, is Uniquely Associated with EF Deficits

The two-group bifactor model of ADHD was employed to partition variance common across all symptom parcels from variance unique to the inattention and hyperactivity/impulsivity domains. All factors were regressed on EF. EF was most strongly associated with the inattention factor ($\beta = -0.24$, $p < 0.01$; Figure 2, left panel; see Supplementary Figure 7a for full model). A weaker but significant association also emerged between EF and general ADHD ($\beta = -0.12$, $p < 0.05$). EF was not significantly associated with hyperactivity/impulsivity.

Next, we estimated the associations between EF and clinically relevant levels of ADHD symptoms. Consistent with our results for continuous measures of inattentive behaviors, individuals who met criteria for inattentive-type ADHD displayed significantly lower overall EF ability ($\beta = -0.17$, $p < 0.01$; Figure 2, right panel). EF was not significantly associated with hyperactive/impulsive- or combined-type ADHD.

Relationship between EF and Inattentive Symptoms is Not Reducible to Processing Speed Differences

We next examined whether the EF-ADHD association was attenuated after including processing speed as a covariate. A negative association between EF and inattention remained after accounting for variance explained by processing speed ($\beta = -0.21$, $p < 0.05$). However, the link between EF and general ADHD was attenuated and no longer significant (Figure 2, left panel; see Supplementary Figure 7b for full model). The unique contribution of processing speed to inattention was not significant ($\beta = -0.16$, $p = 0.10$). Together, EF and processing speed accounted for 12.3% of the variance in inattention ($R^2 = 0.123$, $p < 0.01$).

Individuals who met threshold criteria for combined-type ADHD and inattentive-type ADHD demonstrated lower levels of processing speed ($\beta = -0.33$, $p < 0.05$; $\beta = -0.22$, $p < 0.05$; Supplementary Figures 8a-b). Across diagnostic categories, the association between EF and ADHD was not significant beyond processing speed (Figure 2, right panel).

Association between EF and Inattentive Symptoms is Stable across Sociodemographic Characteristics

Socioeconomic status and demographic factors did not significantly moderate the relation between speed-residualized EF and general or domain-specific ADHD (Figure 3; Supplementary Table 6).

Chapter 4: Discussion

The functional and psychosocial burden associated with a diagnosis of ADHD is profound (Caci et al., 2004). Beyond clinical populations, a substantial proportion of children present with subclinical, yet often debilitating, ADHD symptoms (6.6% in the United States; Fayyad et al., 2017), which are similarly associated with adverse scholastic and functional outcomes (Currie & Stabile, 2004). The cognitive profile of this subclinical population has not been the subject of detailed investigation. The present study examined the association between variation in EF and ADHD, considering both the continuous range of symptom variation and whether individuals met criteria for a clinical diagnosis.

Findings from the present study are consistent with the proposition that executive deficits characterize the cognitive profile of individuals with ADHD, and that EF deficits specifically relate to the inattention domain. This is consistent with neurocognitive theories of ADHD, particularly the dual-pathway model, that identify deficits in executive function as a major pathway to the development of ADHD (Sonuga-Barke, 2003; Barkley, 1997). The specificity of the association between EF and the inattention domain corroborates the conceptualization of ADHD as a heterogeneous disorder. The specific negative link between EF and the inattention domain of ADHD presents an avenue for the application of tests of EF as additional screening tools to identify children struggling with inattentive symptoms of ADHD.

In the current study, executive deficits were not linked to individual differences in hyperactive-impulsive symptoms. While this may seem at odds with previous research implicating response inhibition deficits in hyperactivity/impulsivity behaviors (Piek et al., 2004), it is possible that our focus on a higher-order factor of general executive ability masked such a relationship. Future research would benefit from examining the specificity of the relationship between hyperactive symptoms of ADHD and specific components of EF. A further possibility is that the hyperactivity/impulsivity domain is characterized by a different neuropsychological profile that that of the inattentive domain. Motivational difficulties have been proposed as a potential pathway to the development of hyperactive/impulsive symptoms (Sonuga-Barke, 2003). Future research that jointly considers cognitive and motivational constructs would allow one to test the purported uniqueness of the pathways leading to the development of inattention and hyperactivity/impulsivity.

Supporting existing theories of cognitive deficits in ADHD, the degree of EF deficit in our population-based sample associated with symptom severity (i.e., the number of symptoms reported) within the "normal" range. Furthermore, this relationship held even when controlling for processing speed. On the other hand, deficits in EF among participants who met diagnostic criteria for combined and inattentive-type ADHD were not observed beyond processing speed. One possible explanation for the lack of robust EF deficits in samples meeting clinical cut-offs is that these individuals have processing speed abilities below a certain "critical" threshold. A critically-diminished ability for lower-level cognitive processing might hinder one's ability to effectively employ higher-order cognition, such as EF, in order to inhibit ADHD-related behaviors (Schweitzer, Hanford, & Medoff, 2006; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002).

Alternatively, it may be that characterizing ADHD using clinical cutoffs, rather than continuous symptom counts, leads to an inability to differentiate between lower- and higher-level cognitive processing due to a restriction of variance.

Our results were consistent across all levels of the sociodemographic distribution. Age, sex, socioeconomic status, and race were not found to moderate the EF-ADHD association. Given the broad age range of participants in the study, the lack of age moderation might be surprising. But we note that, whereas hyperactivity/impulsivity symptoms decline with age (Raffaelli et al., 2005), inattentive-type ADHD tends to be a more stable diagnosis over time, and combined-type diagnoses often convert to an inattentive-type diagnosis as hyperactive-impulsive symptoms diminish with age (Hurtig et al., 2007). The specificity of the EF-inattention link might contribute to its consistency across ages. Overall, the present results suggest that the relation between EF and ADHD, and specifically EF and inattention, is invariant across sociodemographic groups, which could broaden identification and assessment efforts currently employed in schools, homes, and community settings.

Our findings should be considered in light of a few limitations. First, the current investigation employed a cross-sectional design, which limits our ability to interpret the direction of effects in the association between EF and ADHD. Second, the wide age range of our participants may have prevented us from identifying differential patterns of associations over development (Happé, Booth, Charlton, & Hughes, 2006). However, the lack of an observed moderating effect of age appears to contradict this proposition. Third, although our model design was guided extensively by previous work (Rhemtulla et al., 2012), alternative approaches to parceling decisions during the modeling of ADHD could have been implemented.

The current study, which found a specific link between cognitive deficits and a continuous measure of ADHD inattention that remains stable across sociodemographic characteristics, widens the scope of ADHD research beyond clinical cut-offs and provides fundamental knowledge likely to inform future research and develop broader assessment strategies and screening tools. Covert inattentive symptoms, rather than overt manifestations of ADHD, appear to be rooted in executive deficits. This highlights the assessment of EF abilities in children presenting with ADHD symptoms as a potential avenue for acquiring key information about the child's cognitive profile and related symptoms.

Figures

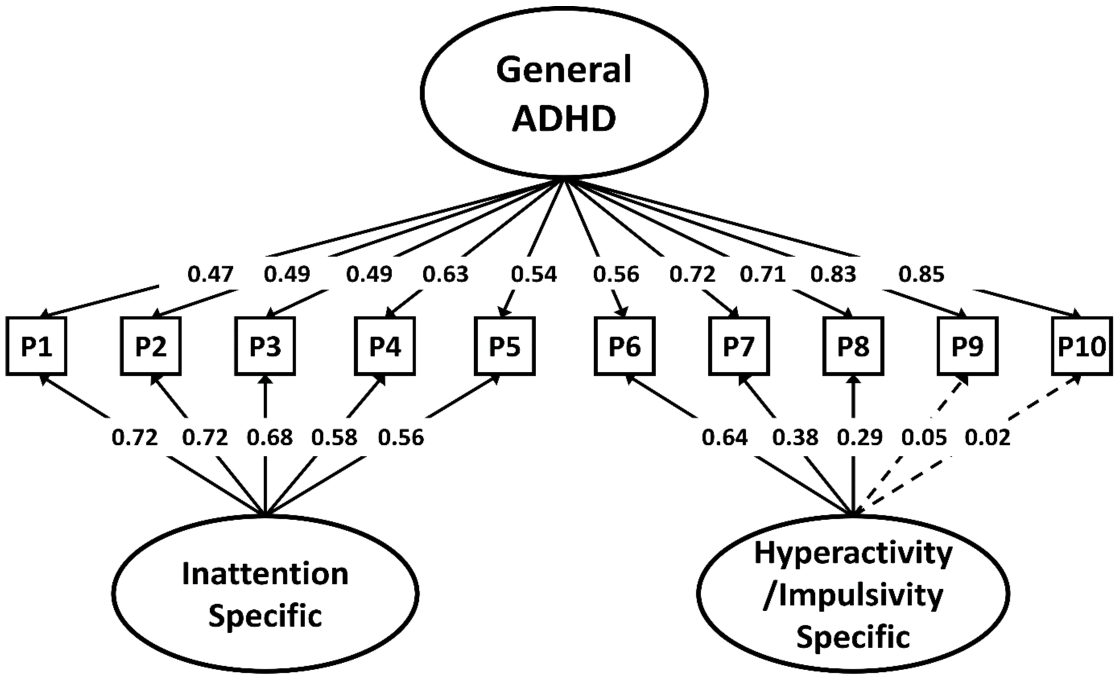


Figure 1. Bifactor model of parent-rated ADHD symptoms. Solid paths are significantly different from zero at $p < .01$. All point estimates are standardized. Items with non-significant loadings were dropped from subsequent analyses.

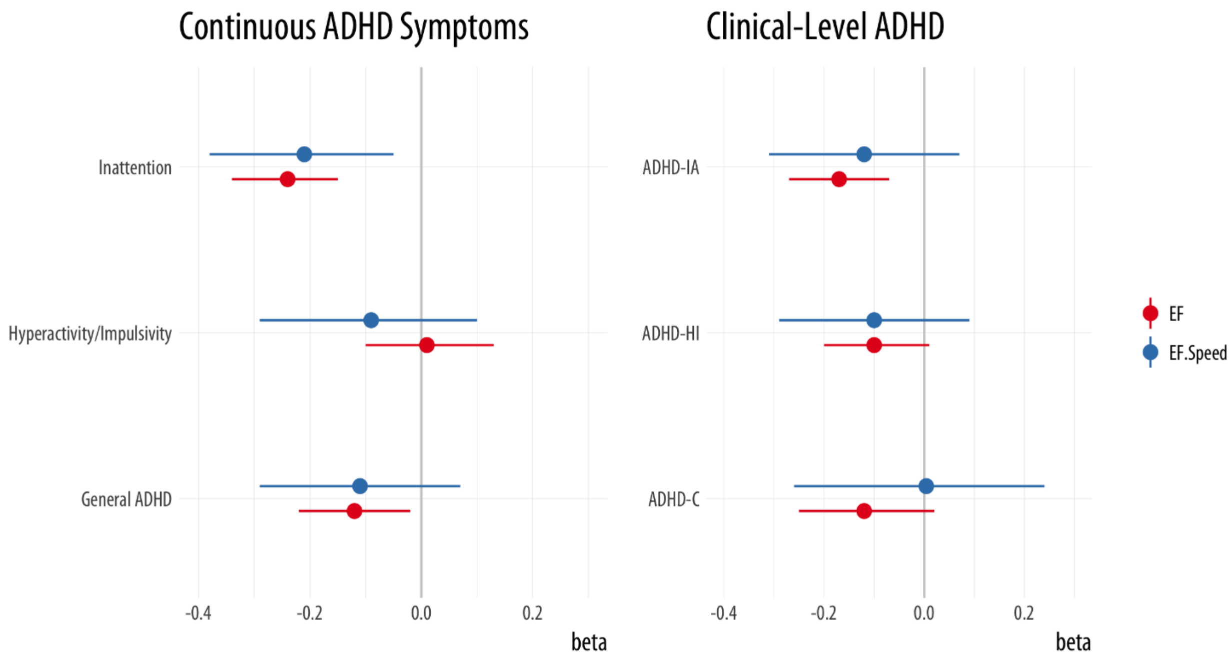


Figure 2. Standardized regression coefficients of ADHD symptom factors and diagnostic ADHD subtypes on EF, before and after adjusting for processing speed differences. Bars represent the 95% confidence intervals.

Note: EF.Speed represents EF controlling for effects of processing speed.

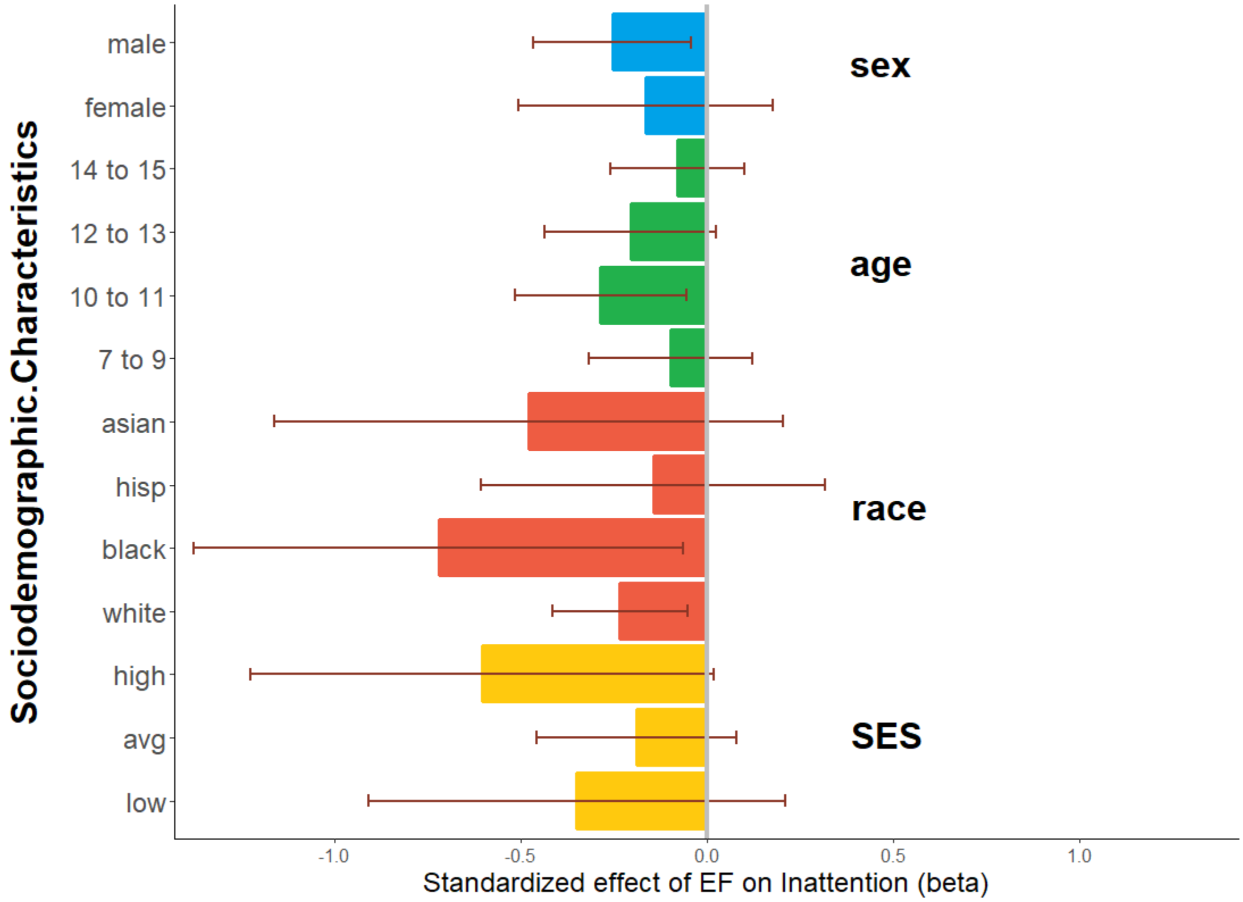


Figure 3. Association between EF test performance and Inattention does not differ across socioeconomic status and demographic groups. Bars represent the 95% confidence intervals.

Appendix

Supplementary Tables

Table 1. Descriptions of the EF battery of tasks.

EF Domain Assessed	Task	Description	References	Reliability (α)
Inhibition	*Animal Stroop*	Participants verbally identify animals based on 3 conditions- • Congruent: Animal's face matches the body • Neutral: Animal face is removed, identification based on animal's body • Incongruent: Animal's face does not match the body, participants are asked to name animal based on the body	Wright, Waterman, Prescott, & Murdoch-Eaton (2003)	.84
Inhibition	*Mickey*	Participants press a button corresponding to the side of the screen that the Mickey Mouse picture flashes. One or two white squares flash before the Mickey appears; participants are told to ignore them. 3 conditions administered- • Congruent: Square flashes on same side as Mickey • Neutral: Squares flash on both sides • Incongruent: Square flashes on opposite side from Mickey	Lee, K., Bull, R., & Ho, R.M.H (2013)	.46
Inhibition	*Stop Signal*	*Stop Signal – Visual* Participants press a button to indicate the direction an arrow is pointing, but are told not to respond when an 'X' appears a short delay after arrow presentation.	Verbruggen & Logan (2008)	.40

Table 1 (*continued*). Descriptions of the EF battery of tasks.

Inhibition	*Stop Signal*	*Stop Signal – Auditory* Same as above, except participants are required to inhibit their response when a tone sounds	Verbruggen & Logan (2008)	.31
Working Memory	*Symmetry Span*	Participants view squares flashing on a grid, and are required to memorize the order of presentation. A symmetry task (indicating whether a geometric picture is symmetrical or not) is used as a distractor on alternating trials (i.e. between each square flashed).	Kane et al. (2004)	.78
Working Memory	*Listening Recall*	Participants listen to single letters and sentences, presented on alternating trials. They are required to both recall the letters presented in order and determine whether the sentence presented makes sense. The number of letters presented increases with each trial set.	Daneman & Carpenter (1980)	.78
Working Memory	*Digit Span - Backwards*	Participants are required to recall and recite increasingly long sets of numbers backward.	Wechsler (2003)	.59
Updating	*Keeping Track*	Participants listen to a list of words associated with between two and six categories. They are required to recall the most recent word from a selected category.	Miyake et al. (2000)	.52
Updating	*2-back/n-back*	Participants view a series of shapes and press a button to indicate whether the current shape matches the shape presented either 1 or 2 trials prior.	Jaeggi et al. (2010);	2 back: .84 n-back: .89
Updating	*Letter Recall*	Participants are presented a sequence of single letters. They are required to identify the last *N* letters, in order of presentation.	Broadway & Engle (2010)	.75

Table 1 (*continued*). Descriptions of the EF battery of tasks.

Switching	*Trail Making* *("Connections")*	A paper-and-pencil task in which participants connect circles containing either letters or numbers according to task rules from 3 conditions- • Numbers: Connect circles in numerical order • Letters: Connect circles in alphabetical order • Number-Letter: Connect numbers and letters in alternating fashion, but still following numerical and alphabetical order (i.e. 1-A-2-B-3-C etc.) • Letter-Number: Connect letters and numbers in alternating fashion, but still following numerical and alphabetical order (i.e. A-1-B-2-C-3 etc.)	Salthouse (2011)	.87
Switching	*Local-Global*	Participants verbally identify letters and shapes composed of smaller letters and shapes, respectively, based on 3 conditions- • Local: Participants name the small letters or shapes that make up the larger figure • Global: Participants name the large letter or shape • Alternating: Participants alternate between naming the smaller and larger letter/shape (based on the rule listed above "small" or "big", respectively)	Miyake et al. (2000)	.73
Switching	*Plus-Minus*	A paper-and-pencil task in which participants are given lists of 2-digit numbers and complete addition and subtraction problems based on 3 conditions- • Addition: Participants add 1 to each number in the first list • Subtraction: Participants subtract 1 to each number in the second list • Alternating: Participants alternate between adding 1 and subtract 1 from each number in the third list	Miyake et al. (2000)	.69

Table 1 (*continued*). Descriptions of the EF battery of tasks.

Switching	*Cognitive Flexibility*	A rule matching game in which participants press a button to indicate which image choice (presented in the middle of the screen) matches a target shape that pops up at the bottom of the screen. The rules are to either match by shape or color.	Baym, Corbett, Wright, & Bunge (2008)	.82

Table 2. Descriptions of the tasks measuring processing speed.

Task	**Description**	**References**	**Reliability (α)**
Letter Comparison	A paper-and-pencil task in which participants compare two letter strings and decide as quickly as possible whether they are the same or different.	Salthouse & Babcock (1991)	0.85
Pattern Comparison	A paper-and-pencil task in which participants compare two geometric patterns and decide as quickly as possible whether they are the same or different.	Salthouse & Babcock (1991)	0.84
Symbol Search	A paper-and pencil task in which participants determine and indicate whether target symbols (simple line drawings) appear in line of various simple symbols.	Wechsler (2003)	0.79

Table 3. Model fit indices for alternate factor structures of ADHD using categorical indicators.

Model	Model Fit Indices					
	χ^2	df	$p(\chi^2)$	RMSEA (95% CI)	CFI	TLI
			Parent-rated ADHD			
One factor: ADHD	2637.43	170	<0.0001	0.100 (0.097-0.103)	0.87	0.82
Two factors: Inatt, Hyp/Imp	822.22	169	<0.0001	0.052 (0.048-0.055)	0.97	0.95
Three factors: Inatt, Hyp, Imp	788.66	167	<0.0001	0.051 (0.047-0.054)	0.97	0.96
Bifactor [2 groups]:						
ADHD, Inatt, Hyp/Imp	**432.88**	**150**	**<0.0001**	**0.036 (0.032-0.040)**	**0.99**	**0.98**
Bifactor [3 groups]:						
ADHD, Inatt, Hyp, Imp	616.93	150	<0.0001	0.046 (0.043-0.050)	0.98	0.96

Note. Models were constructed using categorical indicators. Bold signifies the best-fitting model for each rater. ADHD = Attention-Deficit Hyperactivity Disorder; Inatt = Inattention; Hyp = Hyperactivity; Imp = Impulsivity; χ^2=chi-square; RMSEA = Root Mean Square Error of Approximation; CFI = Comparative Fit Index; TLI = Tucker-Lewis Index

Table 4. Parceling of ADHD items based on rank-ordering of factor loadings onto each specific factor (Inattention and Hyperactivity/Impulsivity).

Item No.	Item	Target Domain	Factor Loading			Parcel No.
			ADHD	**IA**	**H/I**	
7	Has trouble organizing tasks or activities	*Inattention*	0.491**	0.698**		1
6	Fails to complete schoolwork, chores, or tasks	*Inattention*	0.502**	0.692**		
1	Is forgetful in daily activities	*Inattention*	0.467**	0.650**		2
5	Does not follow through on instructions	*Inattention*	0.577**	0.649**		
4	Doesn't pay attention to details; makes careless mistakes	*Inattention*	0.592**	0.612**		3
9	Loses things (e.g. schoolwork, pencils, books, tools, or toys)	*Inattention*	0.481**	0.598**		
8	Has trouble keeping his/her mind on work or play for long	*Inattention*	0.659**	0.554**		4
3	Does not seem to listen to what is being said to him/her	*Inattention*	0.658**	0.496**		
10	Is easily distracted by sights or sounds	*Inattention*	0.616**	0.481**		5
2	Avoids or dislikes things that take a lot of effort and are not fun	*Inattention*	0.473**	0.439**		
12	Blurts out answers before the question has been completed	*Hyper/Impuls*	0.557**		0.639**	6
11	Talks too much	*Hyper/Impuls*	0.495**		0.493**	
20	Interrupts others (e.g. butts into conversations or games)	*Hyper/Impuls*	0.700**		0.419**	7
14	Has difficulty waiting for his/her turn	*Hyper/Impuls*	0.702**		0.413**	
13	Acts as if driven by a motor	*Hyper/Impuls*	0.696**		0.388**	8
16	Is noisy and loud when playing or using free time	*Hyper/Impuls*	0.580**		0.372**	
15	Runs or climbs when he/she is not supposed to	*Hyper/Impuls*	0.721**		0.222**	9
17	Leaves seat when he/she should stay seated	*Hyper/Impuls*	0.852**		0.093	
19	Restless or overactive	*Hyper/Impuls*	0.893**		0.088	10
18	Fidgets or squirms in seat	*Hyper/Impuls*	0.888**		-0.026	

ADHD= Attention-deficit hyperactivity disorder; Group Factors: IA=Inattention, H/I=Hyperactivity/Impulsivity.

**p<0.05; **p<0.001*

Table 5. Model fit indices for alternative factor structures of ADHD using parceled indicators.

Model	Model Fit Indices							
	χ^2	df	p(χ^2)	RMSEA (95% CI)	CFI	TLI	AIC	BIC
Parent-rated ADHD								
One factor: ADHD	1626.75	35	<0.0001	0.18 (0.17-0.19)	0.76	0.55	43383.14	43647.00
Two factors: Inatt, Hyp/Imp	291.65	34	<0.0001	0.07 (0.07-0.08)	0.96	0.92	40942.12	41211.26
Three factors: Inatt, Hyp, Imp	245.00	25	<0.0001	0.08 (0.07-0.09)	0.96	0.92	38582.50	38830.53
Bifactor [2 groups]: ADHD, Inatt, Hyp/Imp	**75.18**	**25**	<0.0001	**0.04 (0.03-0.05)**	**0.99**	**0.98**	**40529.00**	**40845.64**
Bifactor [3 groups]: ADHD, Inatt, Hyp, Imp	117.76	19	<0.0001	0.06 (0.05-0.07)	0.98	0.96	38358.61	38638.30

Note. Models were constructed using parceled indicators that were treated as continuous. Bold signifies the best-fitting model for each rater. ADHD = Attention-Deficit Hyperactivity Disorder; Inatt = Inattention; Hyp = Hyperactivity; Imp = Impulsivity; χ^2=chi-square; RMSEA = Root Mean Square Error of Approximation; CFI = Comparative Fit Index; TLI = Tucker-Lewis Index; AIC= Aikake Information Criterion; BIC= Bayesian information Criterion

Table 6. Moderation of the association between EF and parent-rated ADHD using sociodemographic variables.

Predictor	Inattention		Hyperactivity/ Impulsivity		General ADHD	
	ß	***p***	**ß**	***p***	**ß**	***p***
Processing Speed	-0.20	0.10	0.28	0.08	-0.10	0.43
EF	-0.15	0.01	-0.06	0.34	-0.07	0.23
Speed-residualized EF (rEF)						
Age	0.25	0.01	-0.11	0.21	-0.03	0.72
Sex	-0.06	0.87	-0.53	0.13	0.93	0.01
Race						
White	0.28	0.58	-0.11	0.76	-0.09	0.85
Hispanic	-0.34	0.31	0.48	0.21	0.32	0.49
Black	1.25	0.31	0.46	0.42	0.66	0.41
Asian	0.13	0.81	0.96	0.04	-1.15	0.02
Socioeconomic Status (SES)	0.07	0.22	0.15	0.48	-0.53	0.01
EF × Age	-0.01	0.82	0.05	0.24	-0.06	0.19
EF × Sex	-0.02	0.72	0.04	0.48	-0.05	0.25
EF × Race						
EF × White	-0.09	0.13	-0.11	0.09	0.02	0.77
EF × Hispanic	-0.01	0.85	-0.11	0.08	-0.05	0.40
EF × Black	-0.16	0.06	-0.13	0.05	-0.07	0.45
EF × Asian	-0.02	0.71	-0.13	0.003*	0.01	0.71
EF × SES	-0.04	0.36	-0.08	0.22	0.10	0.02
rEF × Age	-0.01	0.38	0.001	0.96	-0.01	0.59
rEF × Sex	0.02	0.70	0.05	0.46	-0.09	0.14
rEF × Race						
rEF × White	-0.01	0.89	-0.01	0.94	0.03	0.72
rEF × Hispanic	0.02	0.63	-0.03	0.58	-0.04	0.43
rEF × Black	-0.20	0.36	-0.08	0.44	-0.06	0.70
rEF × Asian	-0.05	0.54	-0.18	0.04	0.16	0.03
rEF × SES	-0.004	0.93	-0.05	0.23	0.08	0.03

Note. Coefficients reported are the unstandardized values.

**p<FDR-adjusted threshold for significance*

Supplementary Figures

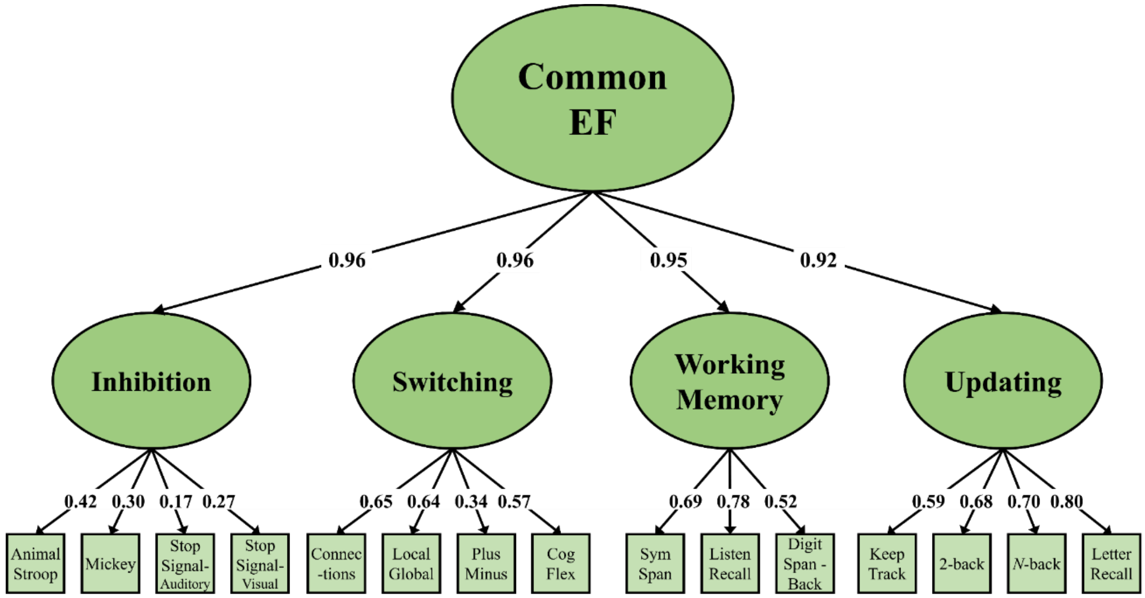


Figure 4. Hierarchical factor structure of the super-ordinate Common EF factor.

Estimates represent standardized factor loadings.

Fit statistics: AIC=41468.6, BIC=41730.5, SRMR=0.04

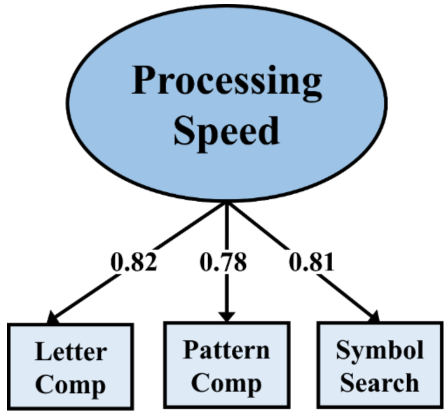


Figure 5. Factor structure of processing speed. Estimates represent standardized factor loadings.

Fit statistics: χ^2 (3)=866.06, p<0.001; RMSEA= 0.00, CFI=1.00, AIC=11198.7, BIC=11246.8, SRMR=0.00

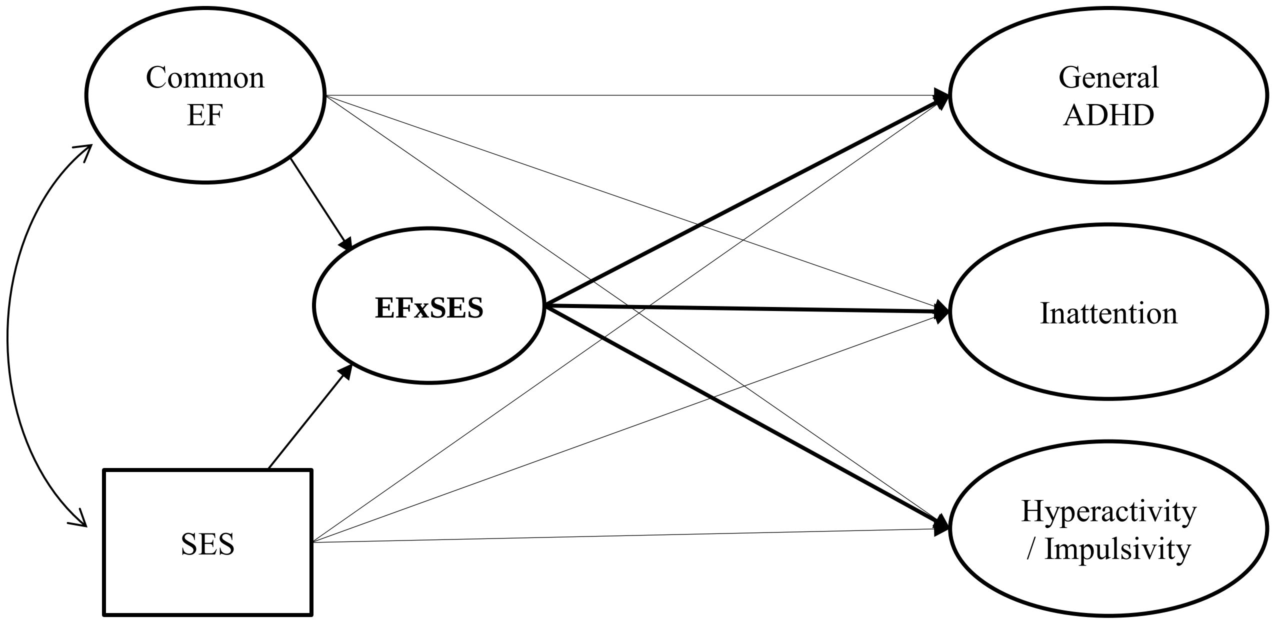


Figure 6. Latent variable interaction model.

Note. Path diagram for the moderation of the EF-ADHD association by socioeconomic status. Bold lines indicate the interaction of EF and SES regressed onto each latent domain of ADHD. The same interaction models were used to assess moderation effects of age, race, and sex on the EF-ADHD association.

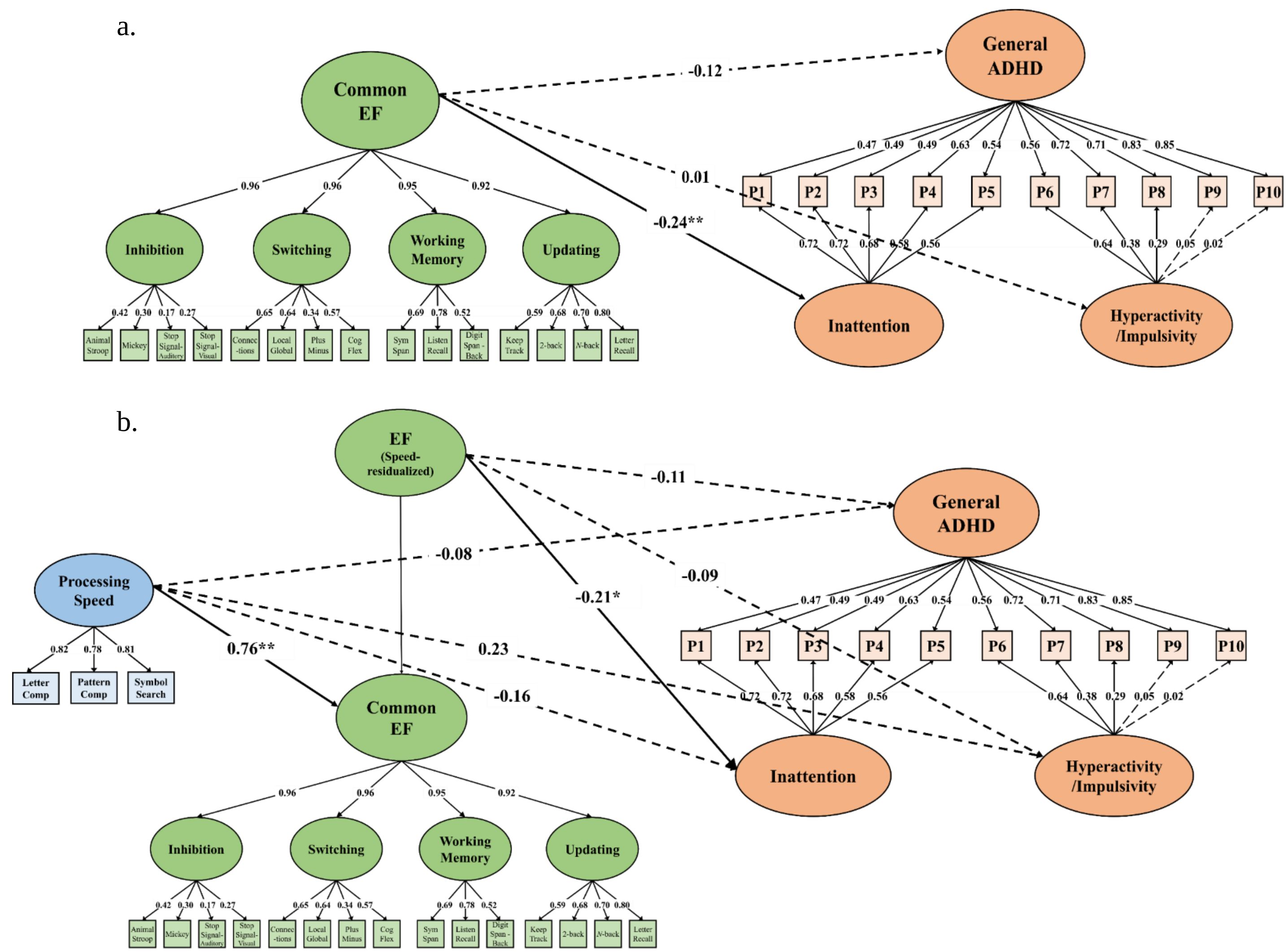
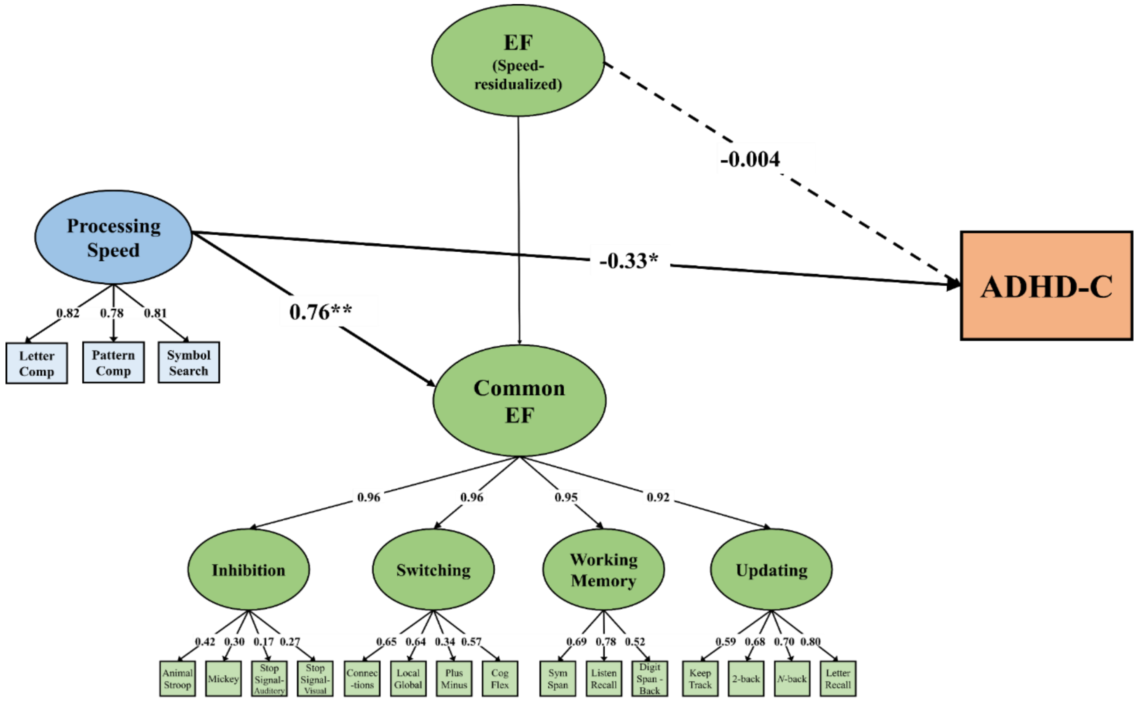


Figure 7. Full model representation of bifactor ADHD regressed onto executive functioning (EF): (a) before and (b) after accounting for the effects of processing speed. All point estimates are standardized regression coefficients. The effects of age and sex were controlled for at the level of first-order factor for EF, and at the indicator-level for ADHD.

Bold lines indicate significance (*p<0.05; **p<0.01).

a.


EF
(Speed-
residualized)
-0.004
Processing
Speed
-0.33*
ADHD-C
0.76**
0.82
0.78
0.81
Letter
Comp
Pattern
Comp
Symbol
Search
Common
EF
0.96
0.96
0.95
0.92
Inhibition
Switching
Working
Memory
Updating
0.42 0.30 0.17 0.27
0.65 0.64 0.34 0.57
0.69 0.78 0.52
0.59 0.68 0.70 0.80
Animal
Stroop
Mickey
Stop
Signal-
Auditory
Stop
Signal-
Visual
Connec
-tions
Local
Global
Plus
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Cog
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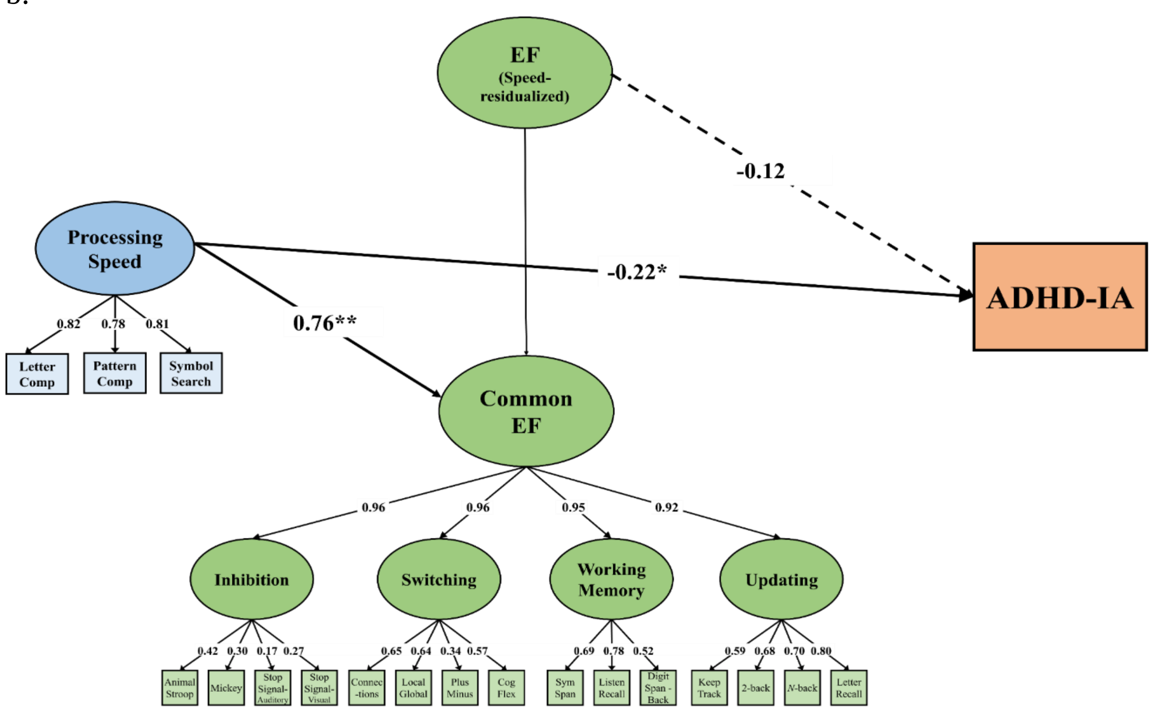
Sym
Span
Listen
Recall
Digit
Span -
Back
Keep
Track
2-back
N-back
Letter
Recall

b.


EF
(Speed-
residualized)
-0.12
Processing
Speed
-0.22*
ADHD-IA
0.76**
0.82
0.78
0.81
Letter
Comp
Pattern
Comp
Symbol
Search
Common
EF
0.96
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0.92
Inhibition
Switching
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Memory
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Figure 8.

c.

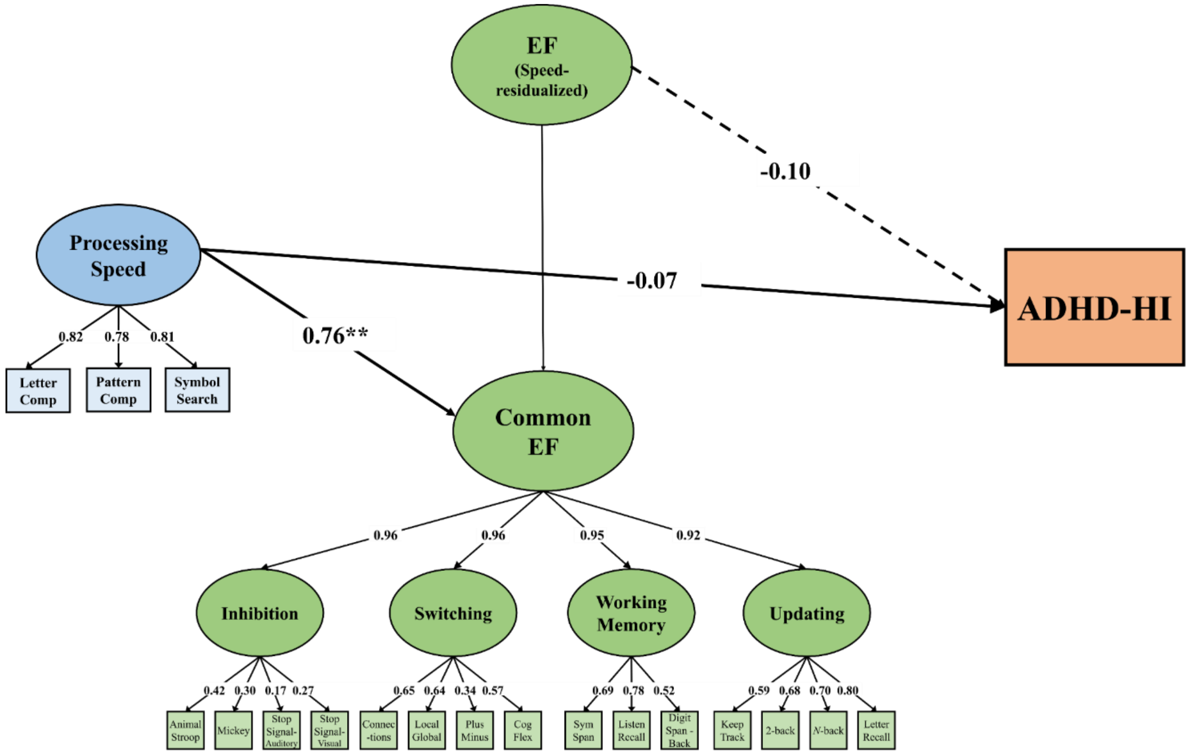

Figure 8. Full model representation of diagnostic categories of ADHD regressed onto processing speed and speed-residualized executive function (EF).

Panel depicts the association between EF, processing speed and: (a) combined-type ADHD (ADHD-C), (b) inattentive-type ADHD (ADHD-IA), and (c) hyperactive/impulsive-type ADHD (ADHD-HI).

The effects of age and sex were controlled for at the level of the factor for processing speed and at the level of first-order factor for EF. All point estimates are standardized regression coefficients. Bold lines indicate significance (**p*<0.05; ***p*<0.01).

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